Effectiveness of Corn Rootworm (Coleoptera: Chrysomelidae) Areawide Pest Management in South Dakota

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ABSTRACT *Diabrotica barberi* Smith & Lawrence and *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae) are serious pests of maize, *Zea mays* L. To reduce the amount of toxicants released into the environment, the Agricultural Research Service implemented a 5-yr (1997–2001) areawide pest management program in five geographic locations, including one in South Dakota. The objective was to use integrated pest management tactics to suppress adult *Diabrotica* populations over a broad geographic area by using aerially applied semiochemical-baited insecticides. Suppressed populations theoretically should reduce oviposition, limit larval feeding damage to maize roots, and result in fewer beetles emerging in subsequent years. We used emergence cages, sticky traps, and CRW lure traps to monitor adult *D. barberi* and *D. v. virgifera* populations. We sampled for *Diabrotica* eggs, and we determined damage to maize roots. We sampled in several maize fields (control) located near the areawide site. The baited insecticides were effective in reducing adult populations 1 and 2 wk after application, and most remained low for the duration of the maize growing season. Fewer beetles were captured in both sticky and lure traps in the areawide site than in the control site. With a few exceptions, egg counts, adult emergence, and maize root damage were similar between the areawide and control sites; however, maize roots had greater fresh weight in the control site. Although not all goals were accomplished, when considering the amount of toxicant released into the environment, using semiochemical-baited insecticides to suppress adult pest *Diabrotica* populations seems to be an effective areawide management tool.

KEY WORDS *Diabrotica*, IPM, landscape, semiochemical baits

The northern (*Diabrotica barberi* Smith & Lawrence) and western corn rootworm (*Diabrotica virgifera virgifera* LeConte) (Coleoptera: Chrysomelidae) are serious pests of maize, *Zea mays* L., in the Corn Belt (Kantack et al. 1970, Metcalf 1986). Traditional control methods include crop rotation, soil insecticides applied at planting, and aerially applied insecticides (Levine and Oloumi-Sadeghi 1991, Sutter and Lance 1991). However, insecticides often are used unnecessarily, which has promoted environmental (i.e., runoff, groundwater alterations), safety (i.e., handling), and economic concerns (Pimentel et al. 1991, Gray et al. 1993). In addition, corn rootworms have evolved mechanisms negating the efficacy of these management strategies. For example, *D. v. virgifera* has become resistant to soil and aerially applied insecticides in areas where maize annually is grown on the same field (Ball and Weekman 1962, Chio et al. 1978, Metcalf 1986, Levine and Oloumi-Sadeghi 1991, Meinke et al. 1998, Wright et al. 2000). Also, in midwestern areas of the Corn Belt where maize is predominantly grown in rotation with another crop, *D. v. virgifera* females began ovipositing in fields other than maize, presumably hedging that maize will be grown the following year (Onstad et al. 1999, Levine et al. 2002). *D. barberi* also circumvented crop rotation as a control strategy. Instead of the typical 1-yr diapause, many eggs overwinter for two or more years (Chiang 1965, 1973; Krysan et al. 1984, 1986; Levine et al. 1992). Consequently, in a 2-yr crop rotation of maize and another crop, usually soybean, *Glycine max* (L.) Merr., *D. barberi* eggs hatch after 2 yr, and larvae then feed on the maize roots. Therefore, the failures of insecticides and crop rotation as consistent, and economical means of managing *Diabrotica* populations have precipitated a need for new management strategies.

Based on research to minimize the use of insecticides and to help protect the environment, the U.S. Department of Agriculture–Agricultural Research Service organized a 5-yr corn rootworm areawide pest management program in 1996 (Lance and Sutter 1991, 1992; Weissling and Meinke 1991; Chandler and Faust 1998; Sutter and Lance 1991; Sutter et al. 1998; Chandler et al. 2000). The areawide management program was implemented in 1997 in five geographic locations, including four (Illinois/Indiana, Iowa, Kansas, and South Dakota) in the Corn Belt and one in Texas

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(Chandler and Faust 1998, Tollefson 1998, Wilde et al. 1998). Managing practices at these sites began in 1997 and they ended in 2001; however, monitoring *Diabrotica* activity continued in a few maize fields in 2002. This broad-scale approach focused on the management of adult *Diabrotica* populations over a wide geographic area, and it relied on action thresholds to determine the need and appropriate timing for aerial applications of semiochemical-baited insecticide formulations. Conceivably this integrated pest management (IPM) approach would substantially reduce insecticide application and be more environmentally friendly (Chandler and Faust 1998). The history of this program is reviewed by Chandler 2003 and Gerber et al. 2005.

The overall objective of the South Dakota areawide management site was to use IPM tactics to suppress adult *Diabrotica* populations over a broad geographic area by using aerially applied semiochemical-baited insecticides. Suppressed adult populations should reduce female oviposition, which would limit damage to maize roots, and result in fewer beetles emerging in subsequent years. Because the baited insecticide remains active for ≈2 wk after application (Lance and Sutter 1992, Pingel et al. 2001), we wanted to ascertain the overall effectiveness in reducing adult *D. barberi* and *D. v. virgifera* populations 1 and 2 wk after insecticide application for each of the 5 yr in the South Dakota management site. We also wanted to compare *D. barberi* and *D. v. virgifera* population dynamics and root damage within the areawide site to a companion control site, which used traditional crop rotation and soil insecticides as population control strategies.

Materials and Methods

Study Area Description. The South Dakota Corn Rootworm Areawide management site was located in Brookings county of east-central South Dakota, which is in the western section of the Corn Belt (Universal Transverse Mercator coordinates for Zone 14N, NW corner 681127e 4911981n, NE corner 687618e 4912125n, SW corner 681317e 4905524w, and SE corner 687768e 4905671n). The study site is within the tallgrass prairie region of the northern Great Plains (Kaul 1986), and it encompassed 41.4 km^2 in a historically dominated mosaic of maize–soybean rotation (Beckler et al. 2004, 2005; French et al. 2004). During the 5-yr study (1997–2001), this area averaged 60 maize and soybean fields each year, with field sizes varying from ≈5 to 60 ha (Table 1). Maize fields were classified as continuous maize, first-year maize, mixed, and other maize. Continuous maize were fields in which maize had been planted at least 1 yr previously, first-year maize were fields that had been in a different crop the previous year, mixed maize were fields that contained a portion of both continuous and first-year maize, and other maize were fields containing small plots or sweet maize (Fig. 1). Over the 5 yr, the mixed and other maize fields made up small proportions of the site.

Table 1. Shown are the numbers of continuous, first-year, mixed, and all maize fields with total hectares occupied from 1996 to 2002 in the South Dakota corn rootworm areawide management site

Yr	Maize type	No. fields	No. ha	Fields sprayed[a]	Ha sprayed	% fields	% ha[b]
1996	Continuous	16	347	0	0	0	0
	First-year	29	654	0	0	0	0
	All	51	1,204	0	0	0	0
1997	Continuous	12	316	7	232	58	73
	First-year	41	938	10	238	24	25
	All	60	1,352	18	533	30	39
1998	Continuous	10	282	7 (5)	486	70	172
	First-year	49	962	16	305	33	32
	All	73	1,370	25	841	34	61
1999	Continuous	11	243	8 (2)	299	73	123
	First-year	43	989	21 (2)	556	49	56
	All	60	1,278	29	855	48	67
2000	Continuous	8	158	6 (2)	252	75	159
	First-year	48	1,088	17 (3)	590	35	54
	All	59	1,303	23	878	39	67
2001	Continuous	4	78	3 (2)	131	75	168
	First-year	42	1,048	22	571	52	54
	All	48	1,133	25	702	52	62
2002[c]	First-year	7	208	0	0	0	0

Also shown are the number and percentages of fields and hectares sprayed by maize type for 1997–2002.
[a] Numbers in parentheses indicates fields resprayed.
[b] Percentage includes acreage resprayed.
[c] Maize fields were monitored for *Diabrotica* spp. activity, and value includes only maize fields with sticky traps, emergence traps, or both.

There were about five control maize fields each year that were located <10 km to the south of the management site (Table 2). These fields varied from 12 to 64 ha, and they included a mixture of continuous and first-year maize. Many of these fields were managed for corn rootworms with soil insecticides applied at planting. From 1997 to 2001, maize planting dates were typical for this area, with most fields being planted from mid-April to mid-May in both the areawide and control sites (Fig. 2). In 2002, a few maize fields were monitored within the areawide site, and only one first-year maize field was monitored in the control site.

Trap Collection. Three different trap types were used to capture adult *D. barberi* and *D. v. virgifera.* Adult activity of *D. barberi* and *D. v. virgifera* were monitored weekly using two trap types; Pherocon AM yellow sticky traps (Trécé Inc., Adair, OK) (Hein and Tollefson 1985, Tollefson 1986, O'Neal et al. 2001) and Pherocon CRW kairomone lure traps (#8279 in 1997, #8391 in 1998–2001) (Trécé Inc.) (Whitworth et al. 2002). These sticky and lure traps were placed randomly in alternating pairs (a pair being one sticky and one lure trap) in 55–62 maize fields beginning ≈60 m into the maize fields past the border rows and thereafter ≈60 m apart along either one or two transects during late June to early July of each year, depending on weather conditions and beetle emergence onset. The 60-m distance between sticky and lure traps was sufficient to ensure that lure traps did not interfere with sticky trap captures (Lance 1993). The sticky traps (0.2 by 0.3 m; 0.06 m^2) were clamped onto wooden lath strips placed between maize rows in each field, and they were positioned at ear height of the

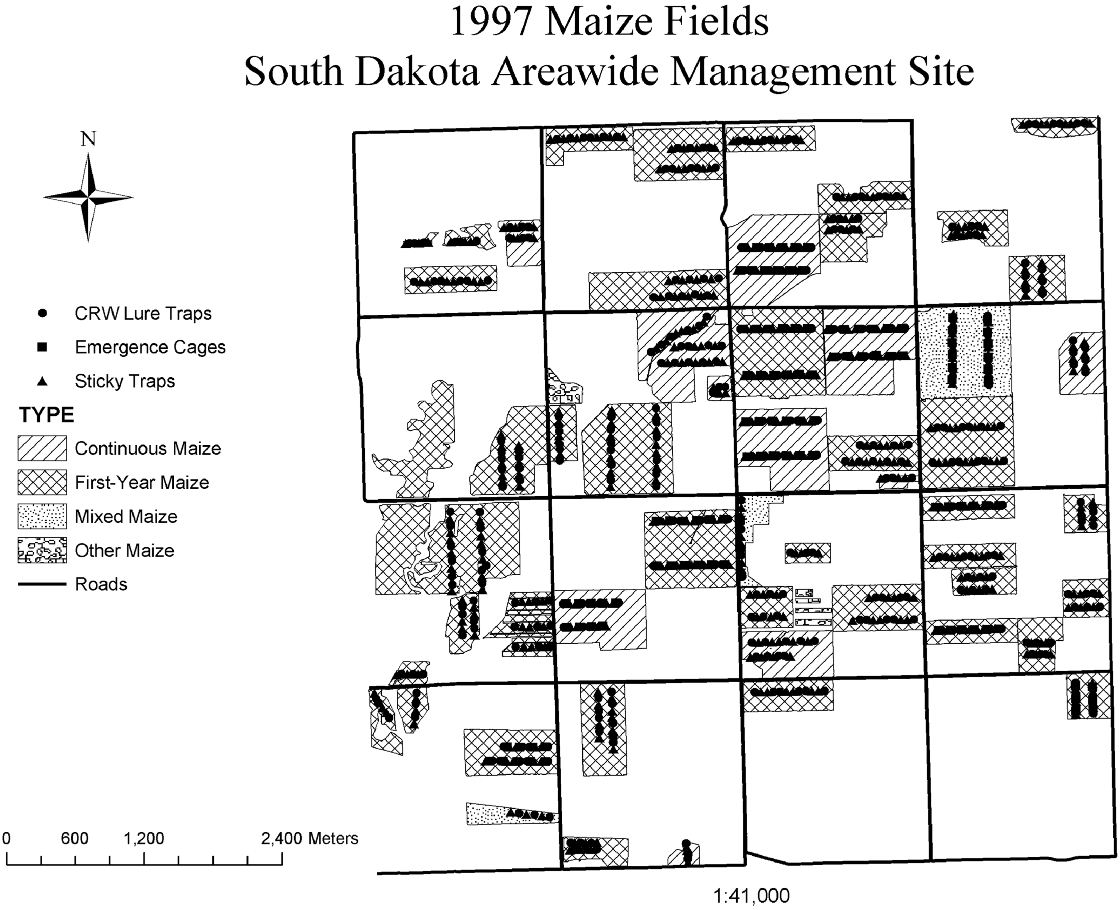

Fig. 1. Depicted is a map showing the location and types of maize fields, roads, and traps in the 1997 South Dakota corn rootworm areawide management site.

maize plant, or ≈1 m above the soil surface. As beetles flew through the field, they were captured on the adhesive surface of the trap. We replaced the sticky traps each week for ≈10 wk and returned them to the laboratory. Sticky traps were stored in the freezer for later processing. When processing sticky traps, all *D. barberi* and *D. v. virgifera* beetles were counted and then removed from the adhesive surface of the trap. The first 50 beetles removed from the trap were sexed based on the supra-anal plate in males (White 1977).

Each lure trap contained a chemical attractant (1,500 mg of eugenol in #8279 and 750 mg of eugenol plus 750 mg of 4-methoxycinnamaldehyde in #8391) located on the outside of the trap chamber, and a stun pill located within the trap chamber. The stun pill was composed of a cucurbitacin (buffalo gourd, *Cucurbita foetidissima* H.B.K.) to stimulate feeding and 3.9% carbaryl to kill the beetles (Trécé Inc.). The lure traps were tied to the maize stalk at ear height or ≈1 m above the soil surface. All *D. barberi* and *D. v. virgifera* beetles were removed weekly for ≈10 wk from each lure trap and placed into an individual 10.2- by 15.2-cm plastic bag. These bags were returned to the laboratory and stored in the freezer for later processing. Lure traps were not used in 2002.

Over the 5-yr, emergence cages were placed in 11–16 randomly chosen maize fields in the areawide site and in all control fields. These cages were positioned ≈ 30 m between the adult monitoring traps and sampled for 6 to 7 wk. Cage construction was similar to that of Musick and Fairchild (1970), Fisher (1980), and Chaddha et al. (1993). Cages were constructed of 26-guage galvanized steel (0.61 by 1.02 m; 0.62 m^2). Cage height varied from one end to the other to facilitate the capture of the beetles, and it ranged from ≈20 cm at the highest end to ≈10 cm at the lowest end. A collecting chamber as described by Chaddha et al. (1993) was attached at the highest end of the cage to easily remove and retrieve beetles. To kill the emerging beetles, we cut Dichlorovos (Vapona No pest strip, Scotts Canada Ltd., Mississauga, ON, Canada) insecticide strips into 1-cm^2 pieces and placed one piece into each collecting chamber. A screen made of wire mesh (eight meshes per cm) covered the top of each cage.

Due, in part, to the number of fields involved in this study and the variability in trap captures of *D. barberi*

Table 2. Shown are the numbers of continuous, first-year, and mixed maize fields with hectares occupied, the insecticide used and rate applied for 1997–2002 in the South Dakota corn rootworm areawide control site

Yr	No. fields	Maize type	No. ha	Insecticide[a]	Rate (kg/ha)
1997	2	Continuous	72	Force	7.3
	1	Continuous	37	Counter	Not reported
	2	Continuous	94	Force	4.5
1998	2	Continuous	54	Fortress	3.7
	2	Continuous	127	Not Reported	
	1	First-year	64	None	
1999	2	Continuous	39	Lorsban	6.4
	1	Continuous	37	Fortress	3.6
	1	Continuous	37	Counter	6.7
	1	First-year	41	None	
2000	2	Continuous	39	Not reported	
	1	Continuous	18	None	
	3	First-year	155	None	
2001	1	Continuous	32	Not reported	
	3	First-year	115	None	
	1	Mixed	38	None	
2002	1	Continuous[b]	38	Fortress	3.7
	6	First-year	212	None	

[a] Force manufactured by Syngenta (Wilmington, DE); Counter manufactured by BASF Canada, Inc. (Florham Park, NJ); Lorsban manufactured by Dow Agrosciences (Frenchs Forest NSW, Australia); and Fortress manufactured by AMVAC Chemical Corporation (Los Angeles, CA).

[b] Only field containing sticky traps and emergence cages; other fields used only in root damage ratings.

and *D. v. virgifera*, sampling intensity was based on field size where the number of transects and traps used in each field varied with field size (Fig. 1). Twelve traps of each kind were placed in fields ≥47 ha, nine in fields 25–46 ha, six in fields 10–24 ha, and three in fields ≤9 ha. One transect was used in fields ≤24 ha, whereas two transects were used in fields >25 ha and they were separated by ≈80 m.

Management Threshold. For most maize fields, a spraying event based on sticky trap adult beetle counts was triggered (action threshold) when 35 or more beetles (both *D. barberi and D. v. virgifera*) were captured in 50% or more of the traps per field over the 7-d period (i.e., five beetles per trap per d). A second spraying event occurred when 28 or more beetles were captured in 50% or more of the sticky traps per field over the weekly trapping period. Due to the size of the study areas and investment by producers, these action thresholds are more conservative than 40 or more beetles captured in each sticky trap over a 7-d sampling period (Hein and Tollefson 1985). Over the 5-yr treatment period, 50 (17%) of the 300 maize fields sampled used lure traps to initiate a spraying event. The spraying event based on lure traps was triggered when 100 or more adults were captured in at least 50% of the traps in a field and when 20–30% of the females were gravid. A second treatment based on lure traps occurred when traps accumulated an average of at least 50 additional adults over a 7-d period in 50% of the traps per field. These latter thresholds for lure traps were subjective, because no published economic thresholds existed and they were intended to compare with sticky traps.

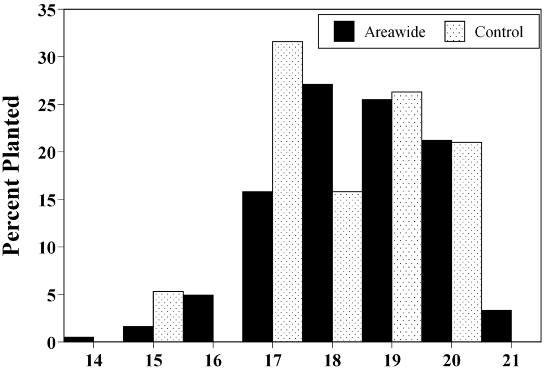

Fig. 2. Combined percentage of planting dates for maize in the South Dakota corn rootworm areawide management site (184 reported dates) and control site (19 reported dates) by week for 1997–2001. Over the 5 yr, week 14 included the first week of April.

Semiochemical Bait Application. During the first 3 yr, SLAM (Micro-Flo Company, Lakeland, FL) was aerially applied at a rate of 561 g/ha to the maize fields when the action threshold was reached. SLAM consisted of 65% of the *Diabrotica* feeding stimulant cucurbitacin, dried buffalo gourd, 13% of the insecticide carbaryl, and 22% other nontoxic ingredients. During 2000 and 2001, problems with SLAM applications emerged. The problem occurred because the method of making SLAM (putting all the materials together) was changed around 2000 due to cost. A less expensive method was used that altered the manner in which the volatiles were released. This slight alteration also resulted in a more difficult product to apply, was less adhesive to the plant surface, and was less efficacious than the original product. Consequently, two new cucurbitacin baits, CIDETRAK CRW (Trécé Inc.) composed of ≈44% cucurbitacin derived from dried buffalo gourd and 56%other nontoxic ingredients and INVITE EC (Florida Food Products, Inc., Eustis, FL) composed of ≈80% cucurbitacin derived from hawkesbury watermelon, *Citrullus vulgaris* Schrad, and 20% other nontoxic ingredients were used as a tank mixture. The insecticide carbaryl was added to the tank mixture at 95 ml/liter of mixture. These were applied at the recommended rates of 9.35 liters/ha for INVITE EC and for CIDETRAK CRW.

Egg Sampling. We used golf course cup cutters (10.5 cm in diameter) to sample for *D. barberi* and *D. v. virgifera* eggs (Ruesink 1986). During autumn and following harvest, we took 12 egg samples from two rows (six in each row) from each maize field in the areawide and control sites from 1997 to 2000. For most fields the rows corresponded to the adult trap rows. For maize fields with single trap rows, we selected rows that were about equidistant from the field boundaries and one another. Sampling began ≈60 m into the maize fields from the border rows, and it continued for about every 60 m. Each sample consisted of three cores at ≈13 cm in depth for ≈3 liters of soil. The three cores were combined and mixed thoroughly. Two, 1-liter subsamples of soil were extracted for egg processing. The soil and eggs were processed using the Illinois egg-separating apparatus (Ruesink 1986). The eggs then were floated in a solution of Epsom salt and water. We counted the eggs and identified them to species by using a Nikon Labophot-2 (Nikon, Tokyo, Japan) phase contrast microscope (Branson et al. 1975).

Maize Root Damage Ratings and Fresh Weight. In the areawide site, maize fields to be sampled for root damage and fresh weight were chosen based on spraying events the previous year. In contrast, all control fields were sampled for root damage and fresh weight. The number of fields chosen in 1998 included 16 first-year corn, seven continuous corn, and zero control fields; in 1999, 19 first-year, seven continuous, and five control fields; in 2000, 10 first-year, four continuous, and six control fields; in 2001, 15 first-year, three continuous, and five control fields; and in 2002, 21 first-year, 0 continuous, and seven control fields. Each year, between 18 and 36 root systems were removed from each field for root damage measurements. The total number of root systems measured was 558 in 1998, 729 in 1999, 531 in 2000, 531 in 2001, and 729 in 2002.

To determine when to sample plants for larval feeding root damage, corn rootworm larval development in continuous maize fields in the management area was monitored. Golf course cup cutters (10.5 cm in diameter) were used to take soil cores from the field every 2 to 3 d starting in early June and continuing until root systems were dug. To sample the soil for larvae, cup cutters were placed directly adjacent to maize plants and pushed into the soil to a depth of ≈12 cm. Cores were placed into buckets and immediately brought back to the laboratory for processing. Large soil aggregates were broken up by hand, and the resulting soil was spread evenly on wire screens (45 cm in width, 60 cm in length, screen mesh size of 2.5 mm^{-2}) suspended over water. These larval separation devices were then placed under incandescent lights for at least 48 h; larvae burrow down to escape the heat and fall through the screen and into the water. Head capsule measurements were used to estimate larval developmental stage (Hammack et al. 2003). Root systems for larval feeding damage measurements were removed from the management area and control fields when a majority of the sampled larval population passed through the third instar and prepupae were present (usually early to mid-July).

The location of root systems to be sampled for larval feeding damage was determined by position of the adult emergence traps. For each trap location, three root systems were removed from the field. Sampling locations were chosen by locating the appropriate trap, skipping two rows to the left or right of the trap, and choosing three maize plants that had similar growth, spacing, and size characteristics. Plants of interest were identified with a tag held to the stem (third internode above the soil) with cable ties. The stem immediately above the tag was removed using branch cutting shears.

A four-tine reinforced potato-digging fork, which was 20 cm in width and 25 cm in length, was used to remove root systems from the soil. The fork, which was positioned ≈10 cm from the base of the plant of interest, was pushed into the ground to a depth of ≈20 cm. Soil containing root systems was removed by pushing down on the handle of the fork, thereby popping a 20-cm-diameter root ball from the soil. Excess soil was removed from the root system by shaking. Root systems were brought back to the laboratory and soaked in water containing sodium hexametaphosphate (350 g per 750 liters of water) for at least 24 h. Sodium hexametaphosphate is a sequestrant that helps disperse the soil from the root system (Gale et al. 2000). Soil remaining on the root system was removed using a high-pressure water wash. Root systems were then stored in plastic bags at 4°C until they were processed for measurements. Rating for larval feeding damage was accomplished using the Iowa 1–6 Damage Scale (Hill and Peters 1971). Stems were removed from the root system by cutting just above the highest node that produced root axes. Root system fresh weight was then measured with a top-loading model 6T410 electronic balance (Ohaus Corporation, Florham Park, NJ).

Statistical Methods. For analysis, fields were classified into spray weeks made up of fields sprayed during the same week. This approach allowed us to estimate the effectiveness of semiochemical-baits at suppressing adult populations. To compare the fields that were sprayed in different weeks, we created a data set that included week 0, which was the week that insecticides were applied. To estimate the efficacy of the treatments we used unpaired *t*-tests to determine statistical differences in the number of beetles captured between 1 (week 1) and 2 (week 2) wk after the spray week (Zar 1984). The statistical tests were conducted for both sticky and lure trap captures. For fields that were sprayed and contained all trap types, parametric correlation analyses were used to ascertain relationships among emergence, sticky, and lure traps. Significance of each correlation coefficient was determined from a Fisher r to z transformation (SAS Institute 1998). We also used unpaired *t*-tests to examine differences in overall trap catches from the areawide and control sites. For each year, differences between the areawide and control sites in emergence, egg counts, root damage ratings, and fresh root weights were determined with unpaired *t*-tests (Zar 1984).

Results

Adult Suppression. Over the 5 yr, the capture rates in sticky traps for both *Diabrotica* spp. reached the action threshold in 120 of the 300 maize fields sampled (Table 1). Only a few fields required an additional treatment. These fields (0 in 1997, five in 1998, four in 1999, five in 2000, and two in 2001) made up 5% of the total fields sampled and 13% of the sprayed fields in the 5-yr period. In addition, five of the 120 fields required a second spray within 2 wk of the initial spray date. In 1997, 1998, and 2000, ≈34% of the maize fields reached

Table 3. Mean ± SE no. of *Diabrotica* spp. (*D. v. virgifera* and *D. barberi*) beetles captured per week in yellow sticky traps during the initial week of insecticide application (week 0), 1 wk after insecticide application (week 1), and 2 wk (week 2) after insecticide application for 1997–2001 in the South Dakota corn rootworm areawide management site

Yr	*Diabrotica* spp.			*n*	% reduction		*t*-test			
	wk 0	wk 1	wk 2		wk 1	wk 2	wk 1	df	wk 2	df[a]
1997	41.7 ± 2.4	17.9 ± 2.4‡	7.1 ± 0.8‡	34	57	83	5.106	32	13.025	32
1998	77.3 ± 12.6	27.6 ± 8.2‡	6.7 ± 1.9‡	50	64	91	5.845	48	11.831	45
1999	69.9 ± 7.6	30.8 ± 4.4‡	13.5 ± 2.4‡	56	56	81	4.661	54	9.152	53
2000	31.8 ± 2.8	10.5 ± 1.2‡	7.6 ± 1.3‡	48	67	76	6.381	46	7.859	45
2001	44.3 ± 5.0	25.5 ± 4.4†	13.8 ± 1.9‡	50	42	69	3.631	48	6.556	39
		D. v. virgifera								
1997	16.8 ± 4.1	5.9 ± 1.5†	1.9 ± 0.6‡	34	65	88	2.769	32	5.458	32
1998	26.0 ± 8.6	8.7 ± 3.7*	1.9 ± 0.9‡	50	67	93	2.265	48	4.390	45
1999	6.6 ± 2.5	2.6 ± 1.1*	0.9 ± 0.4†	56	61	86	1.912	54	3.792	53
2000	10.3 ± 1.6	2.8 ± 0.6‡	1.9 ± 0.5‡	48	73	82	4.660	46	5.770	45
2001	5.5 ± 2.7	2.8 ± 2.0	0.5 ± 0.2†	50	49	91	1.257	48	2.136	39
		D. barberi								
1997	24.9 ± 2.5	12.0 ± 2.0‡	5.2 ± 0.6‡	34	52	79	4.308	32	9.141	32
1998	51.3 ± 5.2	19.0 ± 4.7‡	4.7 ± 1.1‡	50	63	91	6.443	48	14.120	45
1999	63.3 ± 7.1	28.3 ± 4.1‡	12.5 ± 2.3‡	54	55	80	4.377	54	8.722	53
2000	21.5 ± 2.2	7.8 ± 1.0‡	5.7 ± 0.9‡	46	64	73	5.268	46	6.811	45
2001	38.7 ± 3.4	22.6 ± 3.1†	13.3 ± 1.8‡	48	42	66	3.680	48	6.504	39

n, number of fields sprayed for that year. Also shown are percentage of reductions and *t*-tests (*, $P < 0.05$; †, $P < 0.01$; and ‡, $P < 0.001$
[a] Some traps were pulled from fields before this week.

the action thresholds, whereas in 1999 and 2001 closer to 50% of the maize fields reached the action thresholds. The percentage of maize fields sprayed varied by type and year. Over half of the continuous maize fields were sprayed in 1997, whereas ≈75% were sprayed in 1998, 1999, 2000, and 2001. Proportionally, first-year maize fields were sprayed less often than continuous maize fields, ranging from 24 to 49% over the 5 yr.

In each of the 5 yr, and for both sticky and lure traps, the number of *Diabrotica* spp. captured decreased significantly in both 1 and 2 wk after the initial insecticide application (Tables 3 and 4). These patterns of reduced captures after the initial spray also were consistent over the 5 yr for both *D. v. virgifera* and *D. barberi* captured in sticky traps and for *D. barberi* captured in lure traps (Tables 3 and 4). For *D. v. virgifera*, we captured significantly fewer *D. v. virgifera* in lure traps 1 and 2 wk after the initial insecticide application in 1997 and 2000. However, in 1998, 1999, and 2001, we observed a significant reduction in lure captures only during the second week after the initial spray (Table 4).

For those fields that were sprayed and contained all three trap types (emergence, sticky, and lure), we found significant correlations between emergence and sticky traps for all 5 yr (Table 5). However, we found significant correlations between emergence and lure traps in 1997 and 1998 only, although the P value was <0.1 in 1999. Significant correlations between sticky and lure trap captures were observed in all 5 yr (Table 5).

Table 4. Mean ± SE number of *Diabrotica* spp. (*D. v. virgifera* and *D. barberi*) beetles captured per week in lure traps during the initial week of insecticide application (week 0), 1 wk after insecticide application (week 1), and 2 wk (week 2) after insecticide application for 1997–2001 in the South Dakota corn rootworm areawide management site

Yr	*Diabrotica* spp.			*n*	% reduction		*t*-test			
	wk 0	wk 1	wk 2		wk 1	wk 2	wk 1	df	wk 2	df[a]
1997	101.5 ± 23.5	38.8 ± 7.3†	23.9 ± 6.2‡	34	62	76	4.134	32	6.010	32
1998	85.2 ± 16.7	51.8 ± 11.9*	24.0 ± 8.1‡	50	39	72	2.243	48	5.539	48
1999	87.7 ± 12.2	43.2 ± 5.3†	24.8 ± 4.0‡	56	51	72	3.928	54	6.786	54
2000	168.1 ± 21.2	90.1 ± 11.8*	72.6 ± 13.0†	48	46	57	2.547	46	3.633	46
2001	117.9 ± 18.0	62.0 ± 8.2†	33.0 ± 7.2‡	50	47	72	3.334	48	5.986	40
		D. v. virgifera								
1997	81.0 ± 24.2	30.4 ± 7.4*	19.3 ± 6.4†	34	62	76	2.705	32	4.100	32
1998	61.8 ± 15.2	43.9 ± 10.9	21.1 ± 7.5†	50	29	66	0.974	48	3.454	48
1999	30.4 ± 6.8	17.2 ± 4.1	11.4 ± 3.0†	56	43	63	1.395	54	2.679	54
2000	135.3 ± 19.0	71.9 ± 11.4*	55.6 ± 11.6†	48	47	59	2.112	46	3.115	46
2001	51.5 ± 17.3	26.8 ± 6.8	18.3 ± 7.2*	50	48	64	1.335	48	2.684	40
		D. barberi								
1997	20.5 ± 2.6	8.4 ± 1.7‡	4.6 ± 0.7‡	34	59	78	4.475	32	8.030	32
1998	23.4 ± 3.7	7.9 ± 1.5‡	2.9 ± 0.8‡	50	66	88	5.236	48	10.097	48
1999	57.3 ± 8.2	25.9 ± 3.2†	13.4 ± 2.0‡	54	55	77	4.002	54	7.399	54
2000	32.9 ± 5.0	18.2 ± 2.5*	17.0 ± 3.6†	46	45	48	2.509	46	3.205	46
2001	66.5 ± 9.4	35.3 ± 6.8†	14.7 ± 2.7‡	48	47	78	3.050	48	5.889	40

n, number of fields sprayed for that year. Also shown are percentage of reductions and *t*-tests (*, $P < 0.05$; †, $P < 0.01$; and ‡, $P < 0.001$).
[a] Some traps were pulled from fields prior to this week.

Table 5. Correlation coefficients (*r*) and probabilities (*P*) for the relationships between *Diabrotica* spp. (*D. v. virgifera* and *D. barberi*) beetles captured in emergence, yellow sticky, and lure traps for fields that were sprayed and had emergence traps from the South Dakota corn rootworm areawide management site (1997–2001)

Yr	*n*	Emergence-sticky		Emergence-lure		Sticky-lure	
		r	*P*	*r*	*P*	*r*	*P*
1997	36	0.37	0.0240	0.41	0.0130	0.82	<0.0001
1998	50	0.72	<0.0001	0.40	0.0041	0.74	<0.0001
1999	69	0.54	<0.0001	0.22	0.0660	0.80	<0.0001
2000	74	0.45	<0.0001	−0.09	0.4562	0.32	0.0059
2001	83	0.31	0.0041	−0.18	0.1143	0.60	<0.0001

df, number of observations (n) − 2.

Areawide and Control. The 1997–2002 weekly sticky trap captures for *Diabrotica* spp. are in Fig. 3A–F. For most years, the numbers captured in the control site peaked near mid- to late August, whereas the numbers captured in the areawide site peaked in late July to mid-August. Note that in 2002, hailstorms destroyed traps for two consecutive weeks in the only control field. In 1997, 2001, and 2002, the overall mean numbers of *Diabrotica* spp. captured in the control and areawide sites were not significantly different (Table 6). However, in 2001 the numbers captured were very close to significantly different at $P < 0.1$. In 1998, 1999, and 2000, significantly more beetles were captured in

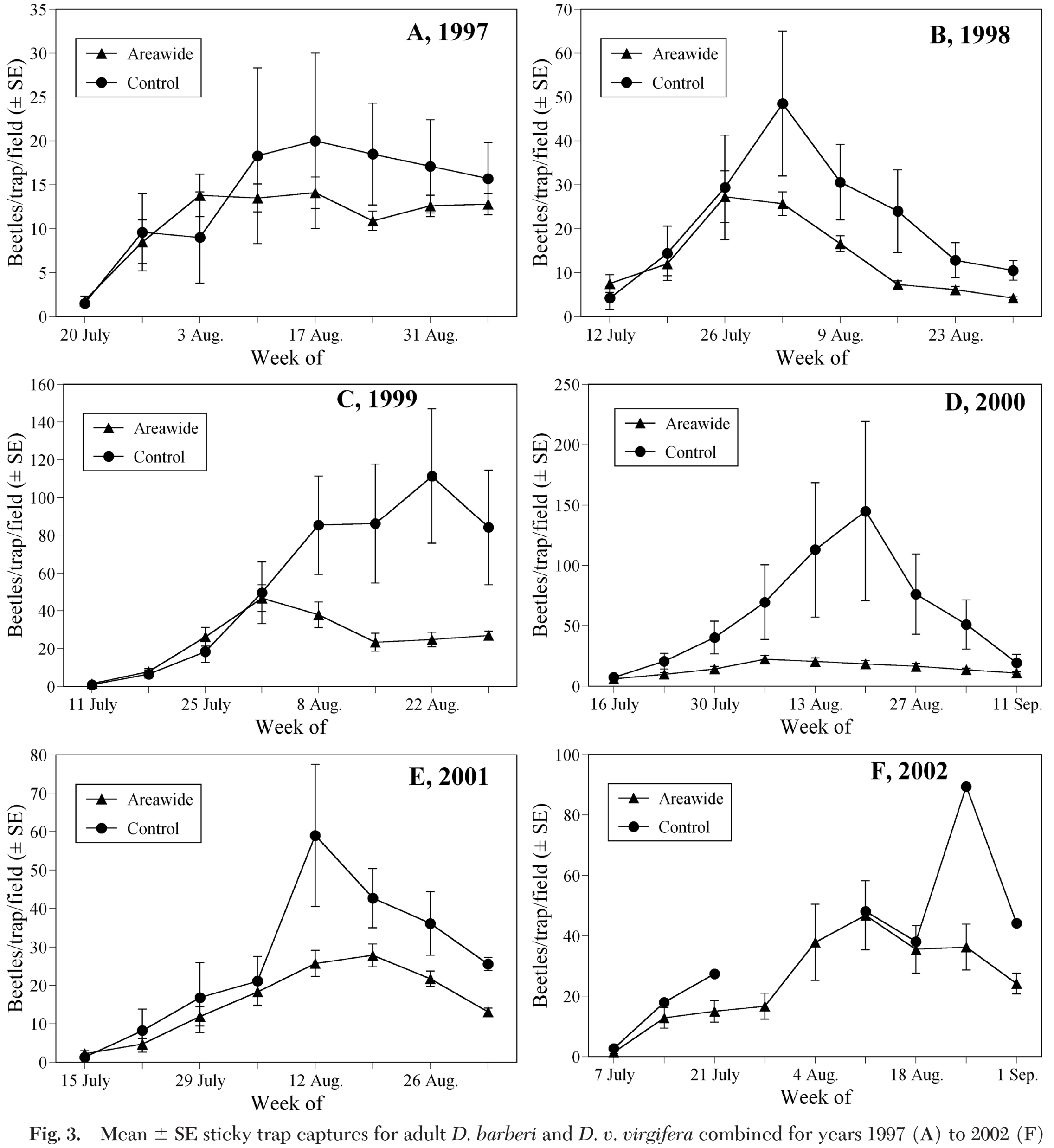

Fig. 3. Mean ± SE sticky trap captures for adult *D. barberi* and *D. v. virgifera* combined for years 1997 (A) to 2002 (F) in the South Dakota corn rootworm areawide management site.

Table 6. Overall mean ± SE number of *Diabrotica* spp. (*D. v. virgifera* and *D. barberi*) beetles captured per field each week in yellow sticky traps (1997–2002) in the South Dakota corn rootworm areawide management and control sites

Yr	*Diabrotica* spp.				*t*-test		
	Areawide	*n*	Control	*n*	*t* value	df	*P* value
1997	10.6 ± 0.6	452	13.4 ± 2.2	41	−1.23	491	0.2208
1998	14.2 ± 1.1	446	21.8 ± 3.6	40	−2.76	484	0.0061
1999	26.7 ± 1.9	389	63.1 ± 10.4	35	−4.07	422	<0.0001
2000	15.3 ± 0.8	474	61.0 ± 12.6	53	−7.18	525	<0.0001
2001	16.8 ± 1.0	335	26.1 ± 4.3	37	−1.79	370	0.0746
2002	24.8 ± 2.8	55	38.3 ± 10.4	7	−1.15	62	0.2529

Also shown are *t*-tests. *n*, number of fields by weeks.

sticky traps placed in control maize fields than those placed in areawide maize fields (Table 6).

The 1997–2001 weekly lure trap captures for *Diabrotica* spp. are in Fig. 4A–E. For most years, the numbers captured in the control site peaked near mid- to late August, whereas the numbers captured in the areawide site peaked in late July to mid-August. In 1997, 1998, and 1999, significantly more beetles were captured in lure traps placed in control maize fields than those placed in areawide maize fields (Table 7). In 2000 and 2001, the overall mean numbers of *Diabrotica* spp. captured in the control and areawide sites were not significantly different (Table 7).

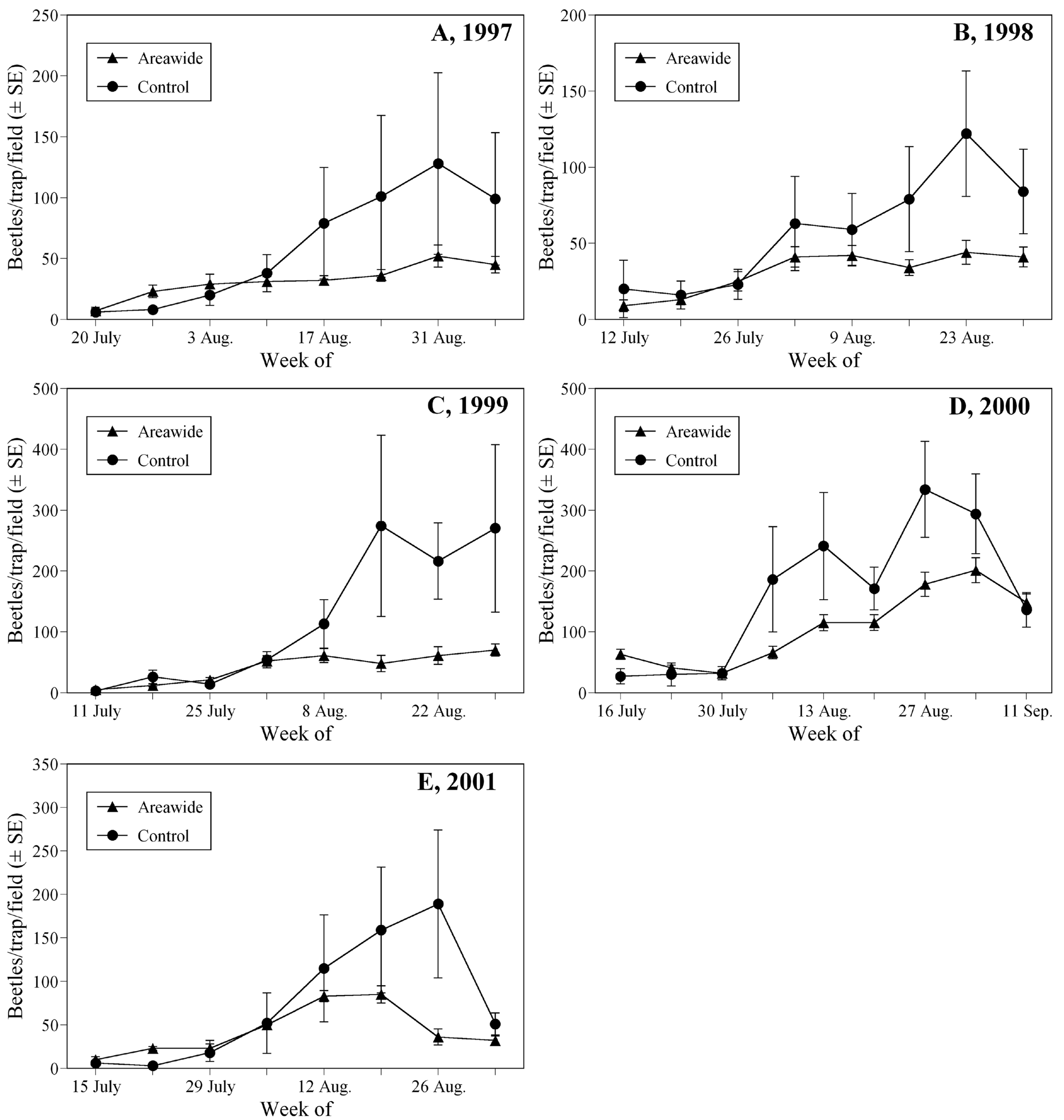

Fig. 4. Mean ± SE lure trap captures for adult *D. barberi* and *D. v. virgifera* combined for 1997 (A) to 2001 (E) in the South Dakota corn rootworm areawide management site.

Table 7. Overall mean ± SE number of *Diabrotica* spp. (*D. v. virgifera* and *D. barberi*) beetles captured per field each week in lure traps for 1997–2001 in the South Dakota corn rootworm areawide management and control sites

Yr	*Diabrotica* spp.				*t*-test		
	Areawide	*n*	Control	*n*	*t*-value	df	*P* value
1997	30.7 ± 2.1	460	60.0 ± 15.8	40	−2.15	498	0.0320
1998	33.4 ± 2.3	446	58.3 ± 10.2	40	−2.33	484	0.0202
1999	45.0 ± 3.8	382	121.3 ± 30.0	40	−2.71	420	0.0071
2000	108.0 ± 5.2	474	161.8 ± 23.2	53	−1.21	525	0.2289
2001	42.8 ± 3.0	334	72.3 ± 18.6	37	−0.62	369	0.5335

Also shown are *t*-tests. *n*, number of fields by weeks.

Egg Sampling and Beetle Emergence. The 1997–2000 egg counts for *Diabrotica* beetles are in Fig. 5A. Over all years, we found 9.7 ± 0.4 (mean ± SE) eggs per liter of soil (n = 2996) in the areawide site, and 8.3 ± 0.7 eggs per liter of soil (n = 480) in the control site (t = 0.81; df = 3,474; P = 0.4172). By year, we found no significant differences between autumn egg counts in the areawide and control sites for years 1997–2000 (t = 0.13, df = 59, P = 0.8988; t = 0.18, df = 21, P = 0.8563; t = 0.39, df = 20, P = 0.7036; and t = 0.20, df = 32, P = 0.8426). The 1997–2002 emergence counts for *Diabrotica* beetles are in Fig. 5B. Over all years, a 28.6 ± 1.2 (mean ± SE) beetles emerged from each cage (n = 630) in the areawide site, whereas 23.9 ± 1.9 beetles emerged from each cage (n = 252) in the control site (t = 3.20, df = 880, P = 0.0014). By year, significantly more beetles emerged from the areawide site than from the control site in 1997 and 1998 (t = 5.16, df = 157, $P < 0.001$; t = 2.10, df = 154, P = 0.0373), but there was no significant differences in emergence between sites for years 1999–2002 (t = 1.20, df = 172, P = 0.2303; t = −0.22, df = 157, P = 0.8297; t = −0.84, df = 20, P = 0.4013; and t = −1.46, df = 67, P = 0.1497).

Maize Root Damage Rating and Fresh Weight. The 1998–2002 maize root damage ratings and root fresh weights are presented in Fig. 5C and D. Over all years, a mean ± SE root damage rating of 1.8 ± 0.03 (n = 819) was observed in the areawide site, whereas 1.7 ± 0.07 (n = 207) was observed in the control site, and these means were not significantly different (t = 1.37; df = 1,024; P = 0.1719). By year, greater root damage ratings were observed on roots from the areawide site than from the control site in 1999 (t = 3.20, df = 241, P = 0.0016). There was no significant differences in root damage ratings between roots obtained from the areawide and control sites in 2000–2002 (t = 0.73, df = 175, $P < 0.4689$; t = 0.99, df = 175, P = 0.9211; t = −1.81, df = 241, P = 0.0718). Over all years, a mean ± SE root fresh weight of 73.9 ± 0.9 g (n = 819) was observed in the areawide site, whereas 83.0 ± 2.0 g (n = 207)

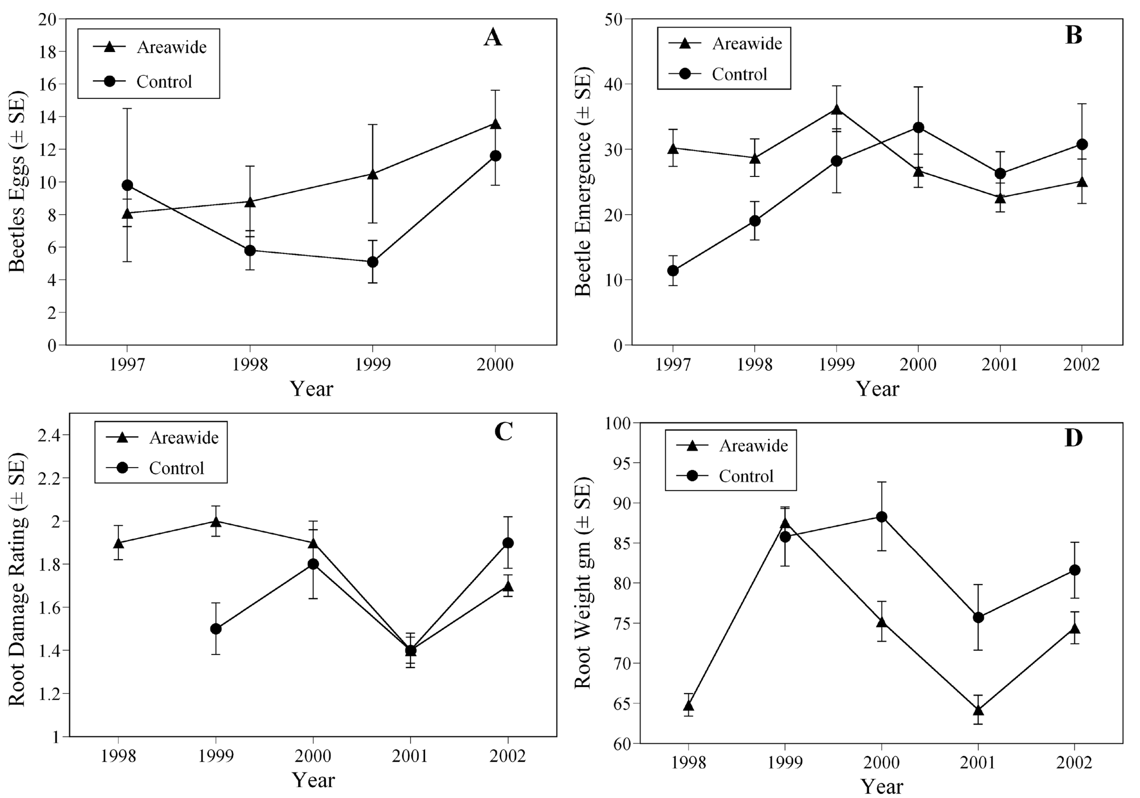

Fig. 5. Mean ± SE *D. barberi* and *D. v. virgifera* eggs per sample for 1997–2000 (A), mean ± SE emergence captures per cage for *D. barberi* and *D. v. virgifera* combined for 1997–2002 (B), mean ± SE root damage ratings (C), and root weight (D) for 1998–2002 in the South Dakota corn rootworm areawide management site.

was observed in the control site. These means were significantly different ($t = -4.4$; df = 1,024; $P < 0.0001$). By year, there was no significant difference in root weight between those from the areawide and control sites in 1999 ($t = 0.50$, df = 241, $P = 0.6196$). However, fresh weight of roots obtained from the control site were greater than those obtained from the areawide site in 2000–2002 ($t = -2.92$, df = 175, $P = 0.0039$; $t = -2.57$, df = 175, $P = 0.0110$; $t = -2.11$, df = 241, $P = 0.0362$).

Discussion

From 1997 through 2001, 40% (3,809 ha) of the maize fields in the South Dakota areawide site were sprayed with a semiochemical-baited insecticide. This contrasts significantly with the area sprayed in the 41.4 km^2 Illinois/Indiana Corn Rootworm Areawide Management Site, where 29,600 ha (143% of total area) was sprayed over the same 5-yr period (Gerber et al. 2005). In the Illinois/Indiana management site, *D. v. virgifera* females often oviposit in soybean fields (Levine et al. 2002), which were included in the hectarge sprayed. In the Kansas Corn Rootworm Areawide Management Site, the percentage of hectarge exceeding the action threshold averaged 33.5% between 1998 and 2001 (Wilde et al. 2003). Wilde et al. (2003) attributed this low percentage to the action threshold not being reached in first-year maize between 1999 and 2001. In Kansas, *D. v. virgifera* females were not noted to oviposit in arable fields outside of maize and *D. barberi* are not abundant. The proportion of first-year maize fields being sprayed in South Dakota tended to increase with years. This may be due, in part, to the increasingly prevalence of extended diapause in *D. barberi* in South Dakota (Krysan et al. 1984, 1986; Levine et al. 1992).

The aerial applications of the semiochemical baited insecticides reduced both *D. v. virgifera* and *D. barberi* populations 1 and 2 wk after the spraying events in all 5-yr. The reductions in beetles captured occurred in both yellow sticky and CRW lure traps, which indicates that, because there were strong correlations among trap captures, both trap types were useful in triggering spraying events. It is not clear, however, whether both trap types were equally effective in capturing males and females of both species in continuous and first-year maize. The number of beetles captured in most fields also remained below the action threshold throughout the maize growing season. Those few maize fields that required second treatments generally were highly aggregated in the landscape (Beckler et al. 2004, French et al. 2004), and perhaps due to beetle immigration from adjacent or nearby maize fields (Pruess et al. 1974, Lance et al. 1989, Spencer et al. 2005; B.W.F. and L.D.C., unpublished data). In small plots, semiochemical-baited insecticides also decreased both *D. v. virgifera* and *D. barberi* populations after applications (Lance and Sutter 1992, Pingel et al. 2001). However, in these studies beetles frequently reinhabited the plots within 1 to 3 wk after spraying.

Both *D. v. virgifera* and *D. barberi* generally were captured in greater numbers in the control site than in the areawide site in both yellow sticky and CRW lure traps. Using plant counts to assess *D. v. virgifera* populations, Pruess et al. (1974) found fewer beetles in a control site than in a 41.4 km^2 managed site in Nebraska. In their study, however, ultralow volume malathion was aerially applied to the entire area on several occasions, but it was not indicated whether soil insecticides were used in the control site. Soil insecticides often are not used in first-year maize, because crop rotation with maize is intended to manage *Diabrotica* pest populations (Sutter et al. 1989, Levine and Oloumi-Sadeghi 1991, Sutter and Lance 1991). Consequently, with no soil insecticides being applied in first-year maize fields in the control site, coupled with the apparent increase in *D. barberi* populations in first-year maize, this could have attributed to the greater number of beetles being captured in the control site. Another important factor that could have contributed to the differences in number of beetles captured is the proportion of continuous maize fields to total number of maize fields. In the areawide site, the percentage of continuous maize ranged from 20% in 1997 to 8% in 2001, whereas in the control site the percentage ranged from 100% in 1997 to 25% in 2001. Although in southeastern South Dakota the number of *D. barberi* captured in continuous and first-year maize is approximately equal (French et al. 2004), *D. v. virgifera* are captured in much greater numbers in continuous maize rather than first-year maize (Beckler et al. 2004).

Over the 4 yr that *Diabrotica* eggs were sampled during autumn, we found no differences between the number of eggs in the areawide and control sites. However, for the first 2 yr of the areawide management program, the number of adult *Diabrotica* beetles emerging from maize fields in the areawide site exceeded those emerging from the control site. During the four subsequent years, we found no differences in adult emergence between the areawide and control sites. In 1996, most farmers in the areawide site probably used soil insecticides to control *Diabrotica* populations and protect the maize roots, suggesting the absence of soil insecticides in 1997 may have resulted in higher emergence compared with the control site. We had expected egg numbers to decline with time in the areawide site compared with the control site; instead, egg density was not reduced below that of the control site. Other factors such as agronomic, climate, intra- and interspecific competition, and differential mortality and fecundity caused by the toxicants (Naranjo and Sawyer 1987, Sutter et al. 1991, Sutter and Hovland 1995) could have affected beetle fitness, which could have affected oviposition and adult emergence. However, because these factors were not measured in our study, we cannot determine whether they affected our results. Planting dates are known to affect *D. v. virgifera* and *D. barberi* population dynamics (Bergman and Turpin 1984, Musick et al. 1980, Fisher et al. 1991), but planting dates in the areawide and control sites were concentrated in a period of late

April to mid-May. In contrast to our study, Gerber et al. (2005) found that fewer *D. v. virgifera* generally emerged in the Illinois/Indiana areawide management site than in their control site, probably due to their more intense spraying regime in soybean as well as maize fields (see above). Perhaps, as one model suggests (Byers and Castle 2005), had we adjusted the action thresholds so that all maize fields were sprayed in synchrony instead of field by field, then a reduction in egg density and emergence with time may have been observed.

The greatest amount of root damage (equivalent to a root damage rating of 2 on the Iowa 1–6 scale) seen in both the areawide site and the control site did not exceed, or rarely exceeded, the commonly accepted economic injury values of 2.5–3.0 for root feeding damage ratings (Turpin et al. 1972, Levine and Oloumi-Sadeghi 1991, Gray and Steffey 1998). We also evaluated maize root weight, and, except for 1999, found that maize roots from the control site were heavier than those from the areawide site, suggesting that the control maize plants may have compensated with additional root growth more than those maize plants in the areawide site (Gray and Steffey 1998). Differences in production practices (tillage, fertilizer, and plant stand density; Riedell et al. 1991, 1992, 1996) as well as genetic differences across maize hybrids (Riedell and Evenson 1993) have been shown to affect maize root system size. Thus, because root systems were collected across a wide range of field production practices and crop hybrids in the management and control areas, it is possible that this simple interpretation of maize root weight data could be complicated by these factors.

In summary, the aerial application of semiochemical-baited insecticides reduced adult *D. barberi* and *D. v. virgifera* populations below action thresholds, and they generally remained low for the duration of the season. This was evident in both sticky and CRW lure traps. In comparison with the control site, we captured fewer adult beetles in both sticky and CRW lure traps in the areawide site than in the control site. Overall, egg counts and adult emergence were similar between the areawide and control sites, and, with the exception of 1999, maize root damage was similar between the two sites; however, maize roots were generally heavier in the control site. Although not all goals were accomplished, using semiochemical-baited insecticides (which use ≈1/10 active ingredient of toxicant compared with soil insecticides) to suppress adult pest *Diabrotica* populations seems to be an effective areawide management tool. With adjustments to the action thresholds based on species, sex, and maize type, all goals possibly could be realized. This areawide method of managing pest *Diabrotica* populations also could be used to complement insect resistance management for transgenic maize. Compared with soil insecticides, it is a more environmentally friendly tool that could be used to treat refugia or other nontransgenic maize in the Corn Belt as well as in countries outside the United States where nontransgenic maize is grown and pest *Diabrotica* are an economic concern. Another benefit is that the toxicant can be chosen for use in INVITE EC and CIDETRAK, thereby reducing the risk of resistance to a particular toxicant.

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